Synopsis
on

ADVANCING CROP PEST MANAGEMENT USING MATHEMATICAL MODELLING AND CONTROL THEORY

BY

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Agricultural productivity is a cornerstone of food security, economic stability, and rural livelihoods around the world (Mozumdar (2012); Muzari (2016)). However, one of the most persistent threats to crop yield and quality is the infestation of agricultural pests. These pests, which include a wide range of insects, pathogens, and weeds, are responsible for significant crop losses annually—posing challenges not only to individual farmers but also to national economies and global food supply chains. In particular, rice, a staple crop for more than half of the global population, is highly susceptible to pest attacks during various stages of its growth (Savary et al. (2019); Oerke (2006)).

Traditional pest control methods, such as chemical pesticides, have been widely used for decades. While these methods often provide short-term relief from infestations, they come with significant drawbacks, including environmental pollution, the development of pesticide resistance among pests, and adverse effects on non-target species including beneficial predators and pollinators (Pimentel (2005)). Moreover, the overuse of chemical inputs contributes to soil degradation, water contamination, and health risks for farmers and consumers. In response, there has been a growing global emphasis on sustainable agricultural practices that incorporate ecological balance, economic feasibility, and human health (Pretty (2008)). This shift in paradigm has led to the exploration of integrated pest management (IPM) strategies, which combine biological, cultural, physical, and chemical tools in a coordinated way to suppress pest populations below economic thresholds (Deguine et al. (2021)). Mathematical modeling has emerged as a powerful tool in understanding, predicting, and optimizing the complex interactions within crop-pest ecosystems. Through the application of differential equations, optimal control theory, and stability analysis, researchers can evaluate the impact of different intervention strategies and guide policy decisions with quantitative evidence.

Researcher explored an integrated modeling approach to pest control, using a sequence of biological, ecological, and behavioral methods to achieve sustainable crop protection. The study begins with the conservation of beneficial pests through the introduction of natural predators, ensuring ecological stability within the crop ecosystem (Gurr et al. (2017)). It then proceeds to the release of infected pests to regulate harmful pest populations, and gradually incorporates farmer awareness, predator–prey interactions, the Sterile Insect Technique (SIT) as a biological approach to reducing reproductive success (Knipling (1955)), and finally, modern tools such as fungal biopesticides and visual traps (Sharma et al. (2014)). Each control strategy is examined from both a dynamic and

optimal control perspective, with the goal of minimizing pest burden while maintaining ecological balance and economic viability. The susceptible pest class represents helpful insect species contributing positively to crop development and ecological stability. However, a viral pathogen emerging from infected pests spreads within the pest population, threatening the survival of these beneficial insects (Fuxa (2004)). To mitigate this threat, natural predators are introduced as a biological control agent to suppress the infected pest population, thereby limiting the spread of infection and indirectly supporting the growth of the susceptible pest class. The system is governed by nonlinear functional responses that realistically capture both infection transmission and predator–prey interactions (Holling (1959)).
Among the various biological control techniques, the release of infected pests into the ecosystem has emerged as a promising strategy for regulating harmful pest populations. This approach involves introducing pests that have been deliberately infected—either with a pathogen, a sterilizing agent, or a behavior-modifying biological agent—so that they interfere with the reproduction or survivability of the wild pest population. The technique is eco-friendly and self-sustaining, especially when paired with natural predators in the environment (Tan and Chen (2009); Bakhtiar et al. (2022); Anonymous (2024)). In crop-pest-predator systems, the interaction between crops, pests, and natural enemies can be described and analyzed through systems of nonlinear differential equations. These models help capture the temporal evolution of each species' population and provide insights into the conditions under which pests can be effectively controlled. When infected pests are introduced, they serve to reduce the healthy pest population either through competition or by spreading infections that lower fertility or survival rates. The addition of a predator species—such as lady beetles, parasitic wasps, or spiders—adds another layer of natural suppression that can amplify the impact of infected pest releases.

From a mathematical modeling perspective, the key variables in such systems typically include crop biomass, pest population density (healthy and infected), and predator population (Rafikov et al. (2008)). These are modeled using systems of ordinary differential equations, with terms representing birth rates, death rates, infection transmission, predation, and crop consumption. Researchers often analyze equilibrium points and assess their local or global stability, which indicates whether pest populations will settle at a manageable level or grow uncontrollably (Murdoch (1975)). To further improve the effectiveness of such strategies, optimal control theory can be employed. This allows the design of time-dependent control policies—such as the timing and frequency of infected pest releases—that minimize pest density and control costs simultaneously. Pontryagin's Maximum Principle is often used to derive the necessary conditions for optimal control, providing practical guidance for field application (Tan and Chen (2009)). Overall, the incorporation of infected pests and natural predators represents an environmentally sustainable and mathematically tractable method for pest control. This foundational model sets the stage for more complex strategies involving awareness, behavioral changes, and advanced control technologies, all of which will be explored in subsequent sections of this thesis.

While biological strategies such as the release of infected pests and natural predators are crucial for pest suppression, the human element—specifically the awareness and behavior of farmers—plays a vital role in the overall success of pest management efforts. Agricultural awareness refers to the level of knowledge that farmers have regarding pest life

cycles, control methods, ecosystem health, and sustainable farming practices. In many developing agricultural systems, pest outbreaks are exacerbated by delayed responses, misuse of pesticides, or lack of understanding of ecological alternatives. Studies have shown that periodic awareness campaigns and mathematical modeling of farmer behavior significantly improve pest control outcomes (Al Basir et al. (2023); Anwar et al. (2023)). Integrated Pest Management (IPM) frameworks also emphasize the importance of farmer education and participation, combining cultural, biological, and chemical measures for sustainable pest suppression (Bhat et al. (2024)). Empowering farmers with timely and accurate information can therefore influence their decisions and lead to more effective pest control.

Mathematical models that incorporate awareness dynamics attempt to quantify how information dissemination and behavioral change among farmers affect the pest population and crop health (Name (2020)). These models often include additional compartments representing levels of informed and uninformed farmers, or use awareness-dependent functions to modulate the application of control measures. The diffusion of awareness can be modeled similarly to disease spread, influenced by campaigns, peer-to-peer communication, or media. The effect of awareness is typically reflected in the improved implementation of biological controls, better timing of interventions, and reduced reliance on harmful chemicals.

Another important component is nutrient management. Crops with optimal nutrient levels exhibit stronger growth, greater resistance to pest attacks, and quicker recovery from damage. When incorporated into models, nutrients act as a supportive variable that influences crop biomass dynamics and can indirectly affect pest population size. The interaction between nutrient levels, pest infestation, and control efforts leads to more comprehensive and realistic models (Cassman (1999)).

From a theoretical standpoint, models that include awareness and nutrients display complex dynamics such as multiple equilibria, threshold effects, and even oscillatory behavior. Global stability analysis ensures that the system settles into a desirable long-term state under broad initial conditions, while Hopf bifurcation analysis helps identify parameter ranges that can lead to periodic outbreaks or instability (Misra et al. (2019); Kuznetsov (1998)). These phenomena are critical for understanding the non-linear responses often observed in real agricultural systems. By integrating agricultural awareness and nutrient management into pest control models, we recognize the importance of human knowledge and crop health in building resilient farming systems (Heeb et al. (2019)). These social-ecological interactions enrich our modeling framework and provide a bridge between theory and real-world applicability.

The effectiveness of agricultural awareness is not solely dependent on the content delivered to farmers, but also on the timing and frequency of such information. Awareness campaigns—whether conducted through local agricultural officers, community meetings, mobile alerts, or mass media—play a central role in educating farmers about integrated pest management, the use of biocontrol agents, and the avoidance of excessive chemical pesticide use. However, in real-world settings, these campaigns are often delivered at varying intervals, sometimes regularly and sometimes sporadically, depending on resources, outreach planning, or administrative cycles (Peshin and Dhawan (2009)).

From a modeling perspective, the temporal structure of awareness dissemination introduces additional complexity into the dynamics of pest management. Regular campaigns—such as seasonal training or annual workshops—create predictable effects on the system and allow for steady changes in farmer behavior. In contrast, irregular campaigns—triggered by outbreaks or funding availability—can cause sudden, short-term improvements in awareness that may decay over time if not reinforced. Capturing this reality in a mathematical model requires the use of periodic or impulsive control functions, which reflect interventions occurring at fixed or variable time points (Lakshmikantham et al. (1989a); Yang (2001)).

In such models, the awareness variable often grows during a campaign and declines afterward due to forgetfulness or lack of reinforcement. These dynamics are typically governed by delay differential equations or impulsive differential equations. The interaction of these dynamics with pest population growth and crop yield introduces interesting mathematical phenomena such as threshold behavior, oscillations, and long-term cycles (Hale (1993); Misra et al. (2019)). These features are important for understanding why some pest control programs succeed while others fail, even when similar resources are deployed.

Irregular awareness campaigns also interact with other control components. For example, if awareness leads to increased use of infected pests or predators, then the timing mismatch between biological interventions and farmer action may reduce overall effectiveness. Conversely, well-synchronized campaigns can enhance the uptake of control measures and maximize their impact. Mathematical analysis helps identify optimal timing schedules for awareness dissemination and quantify the cost-effectiveness of regular vs. irregular efforts (Lenhart and Workman (2007)). While biological strategies such as the release of infected pests and natural predators are crucial for pest suppression, the human element—specifically the awareness and behavior of farmers—plays a vital role in the overall success of pest management efforts. Agricultural awareness refers to the level of knowledge that farmers have regarding pest life cycles, control methods, ecosystem health, and sustainable farming practices.

In many developing agricultural systems, pest outbreaks are exacerbated by delayed responses, misuse of pesticides, or lack of understanding of ecological alternatives. Studies have shown that periodic awareness campaigns and mathematical modeling of farmer behavior significantly improve pest control outcomes (Al Basir et al. (2023)). Integrated Pest Management (IPM) frameworks also emphasize the importance of farmer education and participation, combining cultural, biological, and chemical measures for sustainable pest suppression (Bhat et al. (2024)). Empowering farmers with timely and accurate information can therefore influence their decisions and lead to more effective pest control. Incorporating the temporal dimension of awareness into pest control models enhances both their realism and practical value. It reflects the real-world constraints of extension services while highlighting the need for sustained, well-timed educational outreach to support other biological and behavioral pest control measures (Anwar et al. (2023)).

Optimal control techniques are again essential in this context. They enable the determination of time-varying strategies for awareness campaigns (e.g., frequency, intensity) and nutrient applications to achieve pest suppression with minimal cost and effort. Con-

trol variables may represent the rate of information dissemination, educational campaign strength, or subsidies for sustainable inputs. The resulting strategies guide policymakers and extension services in designing targeted interventions that empower farmers while preserving ecological balance (Lenhart and Workman (2007)).

Optimal control analysis in this context aims to determine the ideal intensity, duration, and frequency of campaigns that minimize pest levels and maximize crop productivity (Name (2021)). Control variables represent not only the amount of awareness effort applied, but also the timing strategy—such as periodic pulsing or state-triggered interventions Lemmon (2010). These results have important implications for agricultural policy: they guide planners on how often to conduct training programs, how to distribute educational materials, and when to launch campaigns in response to pest trends.

The Sterile Insect Technique (SIT) is widely recognized as one of the most promising and environmentally responsible biological control strategies within modern Integrated Pest Management (Knipling (1955); Dyck et al. (2005)). Rather than relying on poisonous chemicals or broad-spectrum insecticides, SIT suppresses pest populations by interfering with their natural reproductive process. The technique involves the large-scale release of laboratory-reared sterile male insects into the crop field. These sterile males actively compete with fertile males for mating opportunities; however, mating with them produces no viable offspring. As a result, the reproductive success of the pest population declines sharply, ultimately reducing future generations of pests without harming beneficial organisms or the surrounding ecosystem.

SIT is particularly effective for pest species with well-defined reproductive patterns and high mating frequency, such as those infesting rice and other agricultural crops (Kapranas et al. (2022)). Its species-specific nature ensures that non-target organisms, including predators and pollinators, remain unharmed. Furthermore, SIT can be seamlessly integrated with other eco-friendly methods, including entomopathogenic fungi, sterile–wild competition, and visual trapping systems, creating a synergistic multifaceted approach for long-term pest suppression (Bourtzis and Vreysen (2021)). Such combined strategies are especially beneficial for sustainable agriculture, where minimizing chemical input and protecting crop biomass are critical priorities.

Mathematically, the impact of SIT is reflected through modifications in the reproduction terms of classical pest population models (Barclay (2005)). In the developed framework, four interacting populations—crop biomass, female pests, male pests, and sterile male pests—determine the system's overall dynamics. The introduction of sterile males reduces the probability of successful mating between wild males and females, effectively lowering the pest population's basic reproduction number. This in turn influences the rate at which crop biomass recovers. Analytical investigations such as equilibrium analysis, stability assessment, and Hopf bifurcation reveal how SIT intensity can shift the system from persistent pest presence to oscillatory dynamics or eventual suppression (May (1974)).

From a control-theoretic perspective, SIT can be optimized by treating the sterile male release rate as a control variable. Using Pontryagin's Maximum Principle, the optimal timing and intensity of sterile insect release can be determined to minimize pest den-

sity and maximize crop biomass while keeping control costs manageable (Lenhart and Workman (2007)). Such optimal strategies are vital for practical field implementation, especially in resource-limited agricultural environments.

Overall, this modeling framework demonstrates that the Sterile Insect Technique, when supported by optimal control theory, provides a highly effective and economically feasible pest management strategy. By reducing pest populations and promoting sustainable crop production, SIT plays a crucial role in the development of environmentally sound agricultural systems (Knipling (1955); Dyck et al. (2005)). In summary, the Sterile Insect Technique (SIT) offers a biologically safe, mathematically tractable, and ecologically sustainable method for pest control. Its incorporation into mathematical models allows for precise evaluation, threshold analysis, and optimization of release strategies, making it a valuable component of modern sustainable agriculture (May (1974)).

In the final stage of our integrated pest management framework, we incorporate the combined effects of fungal biopesticides and visual traps to achieve an environmentally sustainable and highly targeted pest suppression strategy. Among various entomopathogenic fungi, *Beauveria bassiana* has gained prominence due to its ability to infect and kill a broad range of insect pests while being safe for crops, humans, and beneficial organisms (Sharma et al. (2014); Vega et al. (2012)). When spores of *B. bassiana* come in contact with the pest cuticle, they germinate, penetrate the exoskeleton, and proliferate inside the host body, ultimately causing death. The infection process not only reduces pest density directly but also indirectly suppresses pest reproduction and feeding activities.

Mathematical models that incorporate fungal biocontrol typically divide the pest population into susceptible and infected compartments, similar to epidemiological models. The infection transmission rate depends on environmental factors such as humidity and temperature, as well as the density of fungal spores present in the field. The model's dynamics are represented through nonlinear differential equations that capture infection spread, pest mortality, and the regeneration of fungal spores in the environment. Stability analysis helps determine the conditions under which the pest population can be eradicated or maintained below the economic threshold (Fuxa (2004); Vega et al. (2012)).

To enhance the impact of fungal biocontrol, visual traps are introduced as a mechanical control measure. Visual traps—often coloured panels or light-based devices—attract adult pests through visual stimuli and physically capture or immobilize them. In mathematical terms, the effect of traps can be modeled as an additional removal term that reduces the pest population at a rate proportional to trap efficiency and pest abundance (Cook et al. (2007)). The combined use of fungal infection and visual trapping thus integrates biological lethality with behavioral manipulation.

Optimal control theory provides a systematic way to determine the ideal release rate of fungal spores and the deployment intensity of visual traps. The objective function in such models aims to minimize the total pest density and control cost over a given time horizon, ensuring economic feasibility. The controls may represent the periodic application of fungal formulations and the spatial density or operating time of traps. By applying Pontryagin's Maximum Principle, one can derive necessary conditions for these optimal strategies, balancing ecological impact and resource use (Lenhart and Workman (2007)).

From an ecological standpoint, the integration of *Beauveria bassiana* and visual traps offers several advantages. It reduces the need for chemical insecticides, lowers the risk of pest resistance, and promotes biodiversity within the agroecosystem. Moreover, since visual traps specifically target adult pests, they complement the fungal biocontrol's effect on juvenile and adult stages, ensuring more comprehensive pest suppression (Sharma et al. (2014)).

In summary, the fungal biopesticide–visual trap model represents the culmination of our integrated pest control framework. It embodies a synergy between biological and mechanical interventions, underpinned by mathematical rigor. Through theoretical analysis and optimal control design, this approach provides a sustainable, cost-effective, and scientifically grounded pathway for modern rice pest management.
Optimal control is a mathematical approach used to determine the best possible strategy for guiding a system toward a desired outcome while minimizing cost or effort. It has been successfully applied in many fields, including agriculture, public health, engineering, and environmental science. In pest management, optimal control becomes particularly important because it helps balance two essential objectives: reducing pest populations and minimizing economic or environmental costs. Excessive control actions may harm the ecosystem or increase expenses, while insufficient control can lead to severe crop loss. Therefore, designing time-dependent and well-balanced control strategies is crucial. In this thesis, optimal control is applied to several biological pest management methods—including infected pest release, awareness campaigns, nutrient support, predator introduction, the sterile insect technique, and fungal biopesticides—to identify cost-effective and environmentally sustainable ways to suppress pests while protecting crop productivity.
The thesis is organized into the following chapters.

Chapter 2 develops a pest–predator model with viral infection dynamics, emphasizing the protection of beneficial pests that contribute to agricultural productivity. Natural predators are introduced to suppress infected pests, while nonlinear functional responses capture both infection transmission and predator–prey interactions. Analytical investigations identify three equilibria, namely the susceptible-pest–free, virus-free, and interior equilibrium demonstrating that predator intervention stabilizes coexistence and prevents the extinction of beneficial pests. Numerical simulations further validate the ecological significance of predators in mitigating viral spread and supporting pest recovery.

In chapter 3, we examine pest management through the controlled release of laboratory-infected pests. The model analyzes stability regimes, explores conditions for Hopf bifurcation, and determines optimal release rates that minimize crop damage and control costs. The findings highlight how infected pest releases can maintain populations within acceptable ecological and economic thresholds.

Chapter 4 introduces a dynamic model that employs natural predators as sustainable alternatives to chemical pesticides. The framework integrates pest–predator–nutrient interactions and incorporates farmer awareness, underscoring the role of informed practices in enhancing biological control effectiveness while reducing environmental risks. The proposed model is analysed analytically using stability theory and numerically in Matlab

simulations.

Chapter 5 presents a deterministic model of crop biomass and pest populations under the Sterile Insect Technique (SIT). Four interacting populations—crop biomass, female pests, male pests, and sterile males—are examined for equilibrium and stability properties. Hopf bifurcation analysis reveals oscillatory dynamics, while numerical simulations confirm the efficiency of SIT when combined with optimal control strategies, demonstrating its potential as a cost-effective and environmentally sustainable approach.

In chapter 6, we formulate a generic model for pest control using mating disruption and trapping. Based on ODE-driven compartmental dynamics, the model evaluates pheromone trap efficiency and integrates fungal biocontrol (*Beauveria bassiana*) with visual traps within an Integrated Pest Management (IPM) framework tailored for rice fields. An optimal control problem is then constructed to identify deployment strategies that maximize pest suppression while ensuring ecological and economic sustainability.

Chapter 7 provides a comprehensive summary of this thesis-based research and delineates future directions in the development of mathematical models for crop pest management.

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The Publication List

The work reported in the pre submission presentation is mostly based on the following papers:

1. Pan, S., & Sinha, A. (2025). Dynamical modeling and stability analysis of a pest-predator system with biopesticide intervention and a specific nonlinear functional response. *Proyecciones (Antofagasta)*, 44(6), 887 900.

2. Sinha, A., Chowdhury, J., Raezah, A. A., & Al Basir, F. (2025). A Mathematical Model to Study the Role of Sterile Insect Technique in Crop Pest Control: Dynamics and Optimal Control Study. *Mathematics*, 13(17), 2805.

3. Crop-Pest-Predator dynamics under infected pest release: A double edged strategy modeled with optimal control. (*Communicated*).

4. Crop pests control using awareness based release of infected pests and nutrient management: A dynamics study with optimal control approach. (*Communicated*)

5. An Impulsive Control Framework for Pest Management using Infected Pests, Predators and Agricultural Awareness. (*Communicated*)

6. Global dynamics and optimal control of rice leaf roller pests using Beauveria bassiana fungi and visual traps. (*Communicated*).